# Brain-electric correlates of visual word recognition under natural reading conditions

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von M.Sc. Florian Niefind

Präsident/Präsidentin der Humboldt-Universität zu Berlin:
Prof. Dr. Jan-Hendrik Olbertz

Dekan/Dekanin der Lebenswissenschaftlichen Fakultät:
Prof. Dr. Richard Lucius

| | | |
|---|---|---|
| Gutachter/Gutachterin | 1. | Prof. Dr. Werner Sommer |
| | 2. | Prof. Reinhold Kliegl, PhD |
| | 3. | Prof. Dr. Rasha Abdel Rahman |

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## Abstract

The current dissertation uses co-registration of EEG with eye tracking to study the brain-electric correlates of word processing under natural reading circumstances. ERP research has advanced our understanding of the neuronal mechanisms of word processing greatly but traditionally used the RSVP paradigm that is not ecologically valid. Eye tracking research has greatly advanced our understanding of the coordination of linguistic processing with eye movement execution but provides only indirect insight into the actual brain processes during reading. Three reading experiments were conducted to study a) foveal and parafoveal processing, b) word processing in the form of frequency effects, and c) the impact of eye movement planning and execution on a neuronal as well as behavioral level. A fourth experiment tested the generalizability of the preview effects by replicating preview effects in Chinese sentence reading. Results show a robust effect of parafoveal preview on brain-electric correlates of foveal word recognition in the form of an early effect on the N1 component. The preview effect interacted with word frequency in different ways, revealing interactions between the processing of subsequent words in parafoveal and foveal vision. Preview effects were smaller after low frequency words, showing that parafoveal processing is reduced if foveal processing is complex. Also, parafoveal processing also affected foveal processing: Firstly, by providing preview benefit as described above and secondly, by slowing processing rates after a difficult preview (delayed POF effects). Lastly, foveal word frequency effects were found earlier if valid parafoveal preview had been provided. Preview effects were much stronger if eye movements had to be executed, which is most likely due to pre-saccadic attention shifts. Results show the shortcomings of traditional ERP studies and suggest that research on visual word recognition needs to consider eye movements and parafoveal processing.

## Zusammenfassung

Diese vorliegende Dissertation nutzt Koregistrierung von EEG und Eye-Tracking um neuronale Korrelate der Wortverarbeitung beim natürlichen Lesen zu untersuchen. EKP-Forschung hat unser Verständnis der Wortverarbeitung stark geprägt. Jedoch wird Lesen in EKP-Experimenten üblicherweise im unnatürlichen RSVP Paradigma untersucht. Der Blickbewegungsforschung verdanken wir viele Erkenntnisse über die Koordination von Sprachverarbeitung und Blickbewegungsplanung, allerdings nur auf der Verhaltensebene. Drei Leseexperimente in dieser Arbeit untersuchten a) foveale und parafoveale Wortverarbeitung, b) Wortschwierigkeit in Form von Wortfrequenzeffekten und c) den Einfluss von Blickbewegungen. Ein viertes Experiment untersuchte die Generalisierbarkeit parafovealer Vorverarbeitungs-Effekte (Preview-Effekte), indem diese mit chinesischen Sätzen repliziert wurden. Die Ergebnisse zeigten einen reliablen Effekt parafovealer Vorverarbeitung auf neuronale Korrelate der fovealen Worterkennung in Form eines frühen Effekts auf der N1 Komponente. Interaktionen zwischen dem Preview-Effekt und Wortfrequenz zeigten Wechselwirkungen der Verarbeitung aufeinanderfolgender Worte im fovealen und parafovealen Blickfeld. Preview-Effekte waren schwächer nach Worten mit niedriger Frequenz, was zeigt, wie komplexe foveale Wortverarbeitung Resourcen für parafoveale Information bindet. Andererseits beeinflusste parafoveale Verarbeitung auch die foveale Verarbeitung: Erstens durch den oben beschriebenen Preview-Effekt, zweitens durch eine Verlangsamung der Wortverarbeitungsrate nach schweren Vorschaubedingungen. Außerdem zeigten sich foveale Wortfrequenzeffekte früher nach valider parafovealer Wortvorschau. Der Preview-Effekt war stärker, wenn Blickbewegungen ausgeführt werden mussten. Der Grund hierfür sind verdeckte Aufmerksamkeitsverschiebungen vor einer Sakkade. (EKP-)Forschung zur visuellen Wortverarbeitung sollte zukünftig Blickbewegungen und parafoveale Vorverarbeitung berücksichtigen.

# 1 Introduction

Today more than ever, reading is on the way to become the dominant form of communication in modern western society. Despite the predominance of spoken communication (Auer, 2000), the importance of written text has drastically increased throughout the centuries. The most recent technological advance in this development is the Internet. The world wide web is not only a vast amount of text-based information. It has also blurred the boundary between written and spoken language: We chat, send and receive mails, text and status messages, blog etc. Traditionally spoken forms of communication are taken over by written communication. Therefore, reading is an essential skill that the average human engages in countless times each day and seemingly without effort.
But reading is a complex process to master. It requires the coordination of several different processes:

**Word processing.** The ultimate goal of language is to convey meaning. In order to retrieve the meaning from a string of characters, it is necessary to extract visual features of these characters to identify them. Orthographic processing involves the identification of single letters and n-grams until a whole-word representation is arrived at. At the same time, the word is also processed phonologically. The next step is lexical retrieval, which is followed by semantic access. Conceptions of these processing steps differ in the amount of parallel or serial execution of these steps. One such theory, for example, are cascaded models where the processing of different linguistic levels is essentially serial, but there is partial overlap and bottom-up and top-down influences between the levels (McClelland, 1979; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999).

**Attention allocation across the visual field.** During normal reading, the perceptual span covers multiple words at once (McConkie & Rayner, 1975). Consequently, multiple words can be processed during one fixation, though with different degrees of efficiency. Visual acuity in the central two degrees of the visual field (*fovea*) is highest, but drops off sharply in the *parafoveal* (2-5°) and *peripheral* (>5°) field of vision. Despite this fact, parafoveal information is processed (Rayner, 1998) and thus, there is a necessity to allocate attention to multiple words during one fixation either spatially (parallel processing) or temporally (serial processing).

**Saccade planning and execution.** Saccades are rapid jerk-like eye movements that serve to move new information into the foveal field of vision. Unlike during fixations, visual information is not processed during saccades (Slattery, Angele, & Rayner, 2011). Planning a saccade during reading takes about 150-175 ms (Rayner, Slowiaczek, Clifton, & Bertera, 1983), and is separated into a labile phase where a saccade program can still be aborted and a non-labile phase (last 80 ms) where the program cannot be terminated any more (Becker & Jürgens, 1979). A typical fixation during reading lasts 250 ms on average. The saccade planning starts quite early during the fixation and needs to be coordinated with word processing such that it is not executed before the currently foveated word is sufficiently processed, but still as early as possible.

**Combinatorial language processing.** Language understanding goes beyond retrieving single word meaning. The words in a sentence must be morpho-syntactically analyzed to arrive at a combined meaning, which in turn needs to be integrated into higher-level discourse context. Although such processing is believed to be relatively independent of oculomotor control, it can trigger the need to re-read certain words or passages (e.g. Frazier & Rayner, 1982). This dissertation will not be concerned with such higher-level linguistic processing and it is mentioned here just once for the sake of completeness.

This dissertation uses the recent advance in co-registration of EEG and eye tracking and the methodology of *fixation related brain potentials* (FRPs) to study the brain-electric correlates of this complex coordination process that is reading. On the one hand, eye tracking studies have provided considerable insights into these processes at the behavioral level, evidence about the underlying brain processes is indirect (eye-mind hypothesis). Also, the continuous gaze position measurement is usually segregated into fixation durations and hence does not provide on-line insights (Reingold, Reichle, Glaholt, & Sheridan, 2012). The *event related brain potential* (ERP) literature on reading, on the other hand, does provide a more direct on-line measure, but has not considered eye movement planning and execution. This is due to the fact that eye movements cause corneo-retinal artifacts in the EEG signal. Moreover, words are usually shown one by one and at presentation rates that are much slower than fixation durations during natural reading. The reasoning behind such slow presentation rates is to avoid overlap of successive event-related potentials. The cost of this is that words are processed in relative isolation, both temporally (slow presentation rates) and spatially (no parafoveal preview), even if they are part of a sentence context. FRPs provide the means to finally integrate the past 40 years of eye tracking and ERP research.

Given the complexity of the reading process, this dissertation does necessarily focus on some basic aspects of reading while leaving others unconsidered. Three of the four experiments reported here use word list reading instead of sentence reading. Participants' task was to find animal names within lists of five German nouns per trial. While this task ensures semantic processing of single words (Grainger, Kiyonaga, & Holcomb, 2006), word lists contain no small function words and completely exclude the processes mentioned under 'combinatorial language processing' above. The meaning of the single nouns does not need to be integrated and none of the nouns read is predictable from the prior context, as is the case in sentence reading. Also, the current design excludes complex eye movement patterns such as skipping and regressive eye movements. Skipping is practically excluded even though it is theoretically possible: Due to the lack of context and the absence of small function words, no word can be fully processed economically without looking at it directly. Regressive eye movements are excluded by backward-masking any word after the eyes have left it in reading direction. Oculomotor behavior is thus limited to first pass reading. Lastly, as the coupling of word processing and oculomotor control is of main interest, ERP/FRP effects are of limited interest if they are too late to affect fixation behavior.

The main factors of interest are: Parafoveal processing (preview), word frequency, and saccade execution. *Parafoveal preview* allows pre-processing of a word before it is fixated and thus has the potential to have a major impact on neuronal correlates of that word's foveal processing. *Word frequency* serves as an estimate of how difficult a word is to process. Frequency effects are often assumed to directly mark lexical access of a word. We will discuss the validity of this assumption below. Lexical processing is of interest because it is assumed to be the driving factor of oculomotor control in reading (Reingold et al., 2012). The interaction of preview and frequency is also of major interest because in some reading models (Reingold et al., 2012) pre-processing is assumed to be the main reason that word frequency is processed early enough to affect fixation durations. *Saccade execution* is traditionally excluded from ERP research as it leads to corneoretinal artifacts in the signal. However, saccade preparation can lead to costs as well as benefits in attention allocation that need to be considered if one is to study natural reading. The theoretical background for each of these factors will now be discussed in turn.

## 1.1 Parafoveal processing

A key feature of natural reading is that multiple words are visible during a fixation. Consequently, multiple words can be processed during a single fixation either by allocating attention to them serially (first the foveal word and then the parafoveal word) or in parallel (attention is spatially distributed over the foveal and parafoveal field of vision). McConkie and Rayner (1975) used the *moving window paradigm* to assess the width of the area from which useful information is obtained during reading, the *perceptual span*. In this paradigm, only a certain 'window' of letters around the current fixation is visible to the reader, while the rest is masked. If the window size is smaller than the perceptual span, reading speed is impaired. For English, the perceptual span was found to extend 3-4 letter spaces to the left and 14-15 letter spaces to the right (McConkie & Rayner, 1976, 1975; Rayner & Bertera, 1979). This span is mainly based on visual attention and not visual acuity (Miellet, O'Donnell, & Sereno, 2009). It is reversed in languages with different reading direction such as Hebrew (Pollatsek, Bolozky, Well, & Rayner, 1981) and extends the same amount of words or characters across languages, regardless of their physical extension (3-4 characters in Chinese, Inhoff and Liu, 1998, and 3-4 words in English, Rayner, Castelhano, and Yang, 2009).

While the moving window paradigm shows that parafoveal information is somehow used, the *boundary paradigm* (Rayner, 1975) can be used more effectively to study what kind of information is exactly processed. This paradigm uses an invisible boundary in front of a target word. The target word is masked until the reader's gaze crosses the boundary, upon which the mask changes into the target word. Thus, the mask is only processed parafoveally (during a fixation on the pre-target word), while the target word is only processed foveally. Two principal effects of parafoveal processing can be investigated in this paradigm. First, one can measure fixation durations on the pre-target word with regard to properties of the mask. If the mask is processed parafoveally, it might have an impact on foveal processing of the pre-target word (*parafovea on fovea effect*, henceforth POF). Second, one can measure fixation durations on the target word with regard to relations between the mask and the target. If the mask contains information about the target and this information is processed parafoveally, this should be beneficial to subsequent foveal processing of the target (*preview benefit effect*). The identity preview benefit effect represents a benchmark in eye tracking research on reading: Fixation durations are 20-50 ms shorter after a mask which was identical to the target compared to an unrelated mask. Given an average fixation duration of 250 ms in natural reading, such an effect is remarkably large. All of the experiments in this dissertation include (identity) preview benefit effects. Experiment 2 will additionally be concerned with POF effects.

### 1.1.1 Preview benefit in fixation durations

There have been countless studies on what type of parafoveal information is processed (see Schotter, Angele, & Rayner, 2012, for a review). Though results differ between languages and writing systems to some extent, it is possible to summarize a relatively consistent picture for most linguistic levels of processing. Orthographic preview benefits have been found very reliably across languages (Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; Inhoff, 1987, 1989a, 1989b, 1990; Inhoff & Tousman, 1990; Lima & Inhoff, 1985; Rayner, 1975; White, Johnson, Liversedge, & Rayner, 2008). Rayner, McConkie, and Zola (1980) showed that these effects are not the result of a visual word shape. The study also shows that the facilitation is the result of abstract letter codes and not visual features of the letters since the case of the letters between mask and preview was switched (wOrD - WoRd). Word-initial trigrams play an important role in facilitation (Inhoff, 1989b). Transposed letter previews also lead to preview benefit effects, so letter order is not important (Johnson, Perea, & Rayner, 2007).

Phonological preview benefits have also been found (Pollatsek, Lesch, Morris, & Rayner, 1992, e.g. brane - brain). Note that these effects can only be shown in languages where orthography and phonology are not consistently related, such as English (consider 'though' and 'tough'). Ashby and Rayner (2004) showed that partial previews with a preserved first syllable yield larger preview benefits compared to partial previews with the same number of letters but no complete syllable.

For morphological processing results are mixed across languages. While no effects have been found for Finnish and English, there are findings for Hebrew (Deutsch, Frost, Pollatsek, & Rayner, 2005) and Chinese (Yen, Tsai, Tzeng, & Hung, 2008). This serves to illustrate that parafoveal processing is tuned to be optimal for the specific language being read. As analytic languages such as English do not rely on morphology for grammatic markings, processing morphological aspects is much less beneficial than in synthetic languages, especially those that use prefixes and infixes, which are closer to the foveal visual field.

Lexical preview benefit effects have not been reported in the literature (Schotter et al., 2012). Consequently, apart from cases where a word is skipped, it is not clear whether words are processed lexically in the parafovea during reading. The main problem in this regard is that foveal and parafoveal processing are confounded. While a mask may share letters, phonemes, morphemes, syllables, and meaning with the target, frequency is unique to each word. Risse and Kliegl (2014) separated parafoveal and foveal frequency processing by providing the target with a mask that was either identical, or a word with 'opposite' frequency. Opposite in this case refers to a median split across frequencies. This design orthogonalizes the difficulty of the target, the difficulty of the mask and the validity of the mask. The authors found effects of mask difficulty and mask validity on fixation durations on the target. Crucially, since the mask frequency was only visible in the parafovea, this effect shows that frequency of the parafoveal word is processed.

Semantic preview benefits have not been found consistently across languages. While there are clear effects in Chinese (Yan, Richter, Shu, & Kliegl, 2009; Yan, Risse, Zhou, & Kliegl, 2012; J. Yang, Wang, Tong, & Rayner, 2012), there is almost no evidence of semantic parafoveal processing in alphabetic writing systems. The exceptions are findings for German (Hohenstein, Laubrock, & Kliegl, 2010; Hohenstein & Kliegl, 2014) and one study which has reported preview benefits for synonyms in English (Schotter, 2013). This illustrates that the higher the processing level, the more improbable it is to find preview benefit effects, since this processing is preceded by lower-level processing which in itself takes time. If all processing until the meaning extraction was routinely performed while the target is in the parafovea, the target could routinely be skipped. Yan et al. (2009) argue that the Chinese writing system has a more direct mapping from the character symbol to its meaning due to the pictographical nature of the symbols. Consequently it is possible that semantics can be accessed without thorough phonological and orthographic processing. Skipping rates in Chinese are indeed higher than in Western Script languages (Rayner, Li, Juhasz, & Yan, 2005, 42% vs. 20%), but it is hard to clearly separate such an explanation from the fact that multiple words fall into the fovea in Chinese, since a majority of the words consist of one or two characters only.

It is important to consider that the aforementioned processing levels may well interact with each other. A clear separation that has been implicitly suggested here is not likely to accurately represent linguistic processing. For example, the boundaries between lexical and sub-lexical processing are likely to be blurred by the fact that letter activation limits the amount of lexical candidates (e.g. Inhoff, 1989b), which in turn generates expectancies for other letters (Williams, Perea, Pollatsek, & Rayner, 2006; Barber, Vergara, & Carreiras, 2004).

While most experiments focus on the impact of parafoveal processing on subsequent or preceding foveal processing, the reverse case can also be studied. As attentional resources are limited and must be allocated flexibly between foveal and parafoveal processing, foveal processing difficulty (called *foveal load*) can lead to reduced parafoveal information uptake (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999; White, Rayner, & Liversedge, 2005). These results show that word processing during reading is not isolated. Rather, adjacent words influence each others processing in many ways which are ignored by most ERP studies where words are presented one by one (spatial isolation) and at slow presentation rates (temporal isolation). Experiment 1 of this dissertation will examine the brain-electric correlates of foveal load effects.

### 1.1.2 Brain-electric correlates of the preview benefit

There is very little ERP evidence on parafoveal processing in reading. The most notable exceptions are a series of studies by Barber and colleagues (Barber, Donamayor, Kutas, & Münte, 2010, 2013). These studies used the RSVP-with-flankers paradigm, an extension of the RSVP paradigm where the centrally presented word was flankered by the preceding and the upcoming word in a sentence, thus allowing for parafoveal processing. Both of these studies report parafoveal semantic congruency N400 effects in English as well as German. While this is an interesting finding, it is puzzling that there is no neural correlate of the preview benefit effect. The N400 effect is too late to be behaviorally relevant for fixation durations. Experiment 4 of this dissertation was dedicated to investigate the matter further.

Measuring FRPs, Dimigen, Kliegl, and Sommer (2012) employed the word list reading paradigm used in this dissertation to compare the impact of identical masks to semantically related and unrelated word masks. No semantic preview effects were found in fixation behavior or FRP signals. There was, however, an identity preview effect on the falling flank of the N1 component. N1 amplitudes were reduced after an identical preview compared to the two other conditions, which is why the effect was called *preview positivity*. The effect was lateralized to the left hemisphere and peaked between 200-280 ms. Source analysis suggested a source in the right and left fusiform gyrus with a stronger source in the left hemisphere. Additionally, there was a marginally significant N400 effect of preview. The preview positivity is the effect of main interest in this dissertation, as its latency allows it to be behaviorally relevant.

The N1 component has been suggested to reflect visual expertise for specific domains: While all humans show enhanced N1 amplitudes in response to faces (Maurer, Rossion, & McCandliss, 2008; Rossion, Joyce, Cottrell, & Tarr, 2003), bird experts show enhanced amplitudes in response to bird pictures (Tanaka & Curran, 2001). In the case of reading, part of the N1 reflects an acquired specialization to orthographic stimuli, while the left-lateralized portion of the N1 has been implicated to also reflect automated linguistic processing (Maurer, Blau, Yoncheva, & McCandliss, 2010). Evidence from a variety of methods (intracranial ERPs, fMRI, MEG, and lesion studies) have implicated the N1 to reflect some orthographic and phonological processing (Allison, McCarthy, Nobre, Puce, & Belger, 1994; McCandliss, Cohen, & Dehaene, 2003; Nobre, Allison, & McCarthy, 1994; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). ERP studies consistently found more negative N1 amplitudes for words than for symbols (Bentin et al., 1999; Maurer, Brem, Bucher, & Brandeis, 2005; Maurer, Brandeis, & McCandliss, 2005; Schendan, Ganis, & Kutas, 1998). The source of the N1 is consistently found in the left fusiform gyrus. This area has been labeled the 'visual word form area' by McCandliss et al. (2003), who found that patients with lesions in the left fusiform gyrus are able to read single letters, but not complete words. In addition to sub-lexical processing, N1 amplitudes have also been found to be affected by word frequency (Hauk & Pulvermüller, 2004; Sereno, Rayner, & Posner, 1998; Dimigen, Dambacher, Kliegl, Sommer, & Hauk, in prep.). Taken together, such results are consistent with the notion that the preview positivity reflects differences in sub-lexical orthographic processing and possibly also its interactions with lexical retrieval.

### 1.1.3 POF effects

POF effects have been reliably found on the orthographic level (Drieghe, 2011): Parafoveally presented non-words that contained illegal letter combinations reliably elicit longer fixation durations compared to legal letter strings (Inhoff, Starr, & Shindler, 2000; White, 2008; Drieghe, Rayner, & Pollatsek, 2008). The existence of lexical and semantic POF effects is a topic of controversy. Lexical POF effects have been reported in corpus analyses (Kennedy & Pynte, 2005; Kliegl, Nuthmann, & Engbert, 2006), but many experimental studies have not found positive evidence (Angele & Rayner, 2011; Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Henderson & Ferreira, 1993; Inhoff et al., 2000; Rayner, Juhasz, & Brown, 2007). Some experimental evidence comes from studies on word list reading (Kennedy, 1998, 2000; Kennedy, Pynte, & Ducrot, 2002; Schroyens et al., 1999), which is arguably weaker than natural reading in external validity (Schotter et al., 2012). Risse and Kliegl (2014) argue that the effect of mask difficulty found in their study (see above) is a POF effect which is delayed. As delayed effects are observed for foveal frequency processing it is plausible that they should be observed for parafoveal processing. But as mask validity and mask frequency are usually confounded, the effects cannot be separated from preview benefits in most studies using fixation durations. Experiment 2 of this dissertation applies the design of Risse and Kliegl (2014) to the word list reading to investigate brain-electric correlates of mask frequency.

There have been three studies which looked at neuronal correlates of immediate POF effects (Baccino & Manunta, 2005; Dimigen et al., 2012; Simola, Holmqvist, & Lindgren, 2009). In the study by Dimigen and colleagues (2012) a target word was followed by an identical word, a semantically related word, or an unrelated post-target word. Dimigen et al. found an N400 effect in relation to fixation onset on the target word: N400 amplitudes were most negative for an unrelated post-target word, intermediate for a semantically related word and least negative for the identical word. The authors interpreted these effects as an identity priming N400 and a semantic priming effect, respectively (Rugg, 1985, 1987). The short latency in relation to fixation onset on the post-target word by partial parafoveal pre-processing of that word. However, as the effect occurred 80 ms after a fixation on the post-target word it cannot unambiguously attributed to parafoveal processing.
In another study, Baccino and Manunta (2005) showed a prime and a target word, which had to be fixated in succession, and recorded FRPs in relation to fixations on the prime words. The primes were either semantically related or unrelated to the targets, or a non-word. FRPs to non-words differed from those to the two word conditions as early as 119 ms, coinciding with the N1 component in their recordings. At 215 ms (P2 component) an FRP difference between semantically related and non-related words was found. Simola and colleagues (2009) used the same paradigm, except that they varied whether the target was to the left or the right of the prime. They replicated none of the effects. Instead, they found P2 differences (200-280 ms) between words and non-words, but only if the target was presented in the right visual field. However, none of the latter two studies looked at effects beyond the fixation of the prime word.

## 1.2 Frequency and lexical processing

A major assumption shared by many current models of oculomotor control in reading is that lexical access to the foveated word drives the decision to move the eyes forward either directly (e.g Reichle, Pollatsek, & Rayner, 2006) or impacts it indirectly (e.g. Engbert, Nuthmann, Richter, & Kliegl, 2005). Therefore, the point at which a word is recognized is of special importance among the cognitive stages of word processing. In reading studies, word frequency effects are commonly used as a indicator for lexical access: The rate at which a given word occurs within a language – and thus the average reader's familiarity with it – determines how hard it is to process, regardless of its sub-lexical features and its meaning. The validity of using frequency effects as an indicator of lexical access will be discussed below, but first frequency effects in eye movement and

ERP research shall be reviewed and related.

Foveal fixation times during reading are reliably affected by word frequency (e.g. Kliegl et al., 2006; Rayner, 2009, for a review) and often frequency effects are also visible on subsequent fixations which are sometimes on the next word (e.g. Rayner & Duffy, 1986; Pollatsek, Reichle, Juhasz, Machacek, & Rayner, 2008). Such *spill-over* effects of lexical processing load onto the next word's fixation durations have been used to argue that frequency effects are usually too late to immediately affect the saccade terminating the fixation on the word itself (Deubel, O'Regan, & Radach, 2000; McConkie & S. Yang, 2003). Given the aforementioned saccade planning time of 150-175 ms, lexical access might only be 'in time' to impact extremely long fixations. To test this assumption further, Reingold et al. (2012) recently conducted distributional analyses of fixation durations instead of analyzing mean fixation durations. They found a temporal shift in the entire fixation duration distribution with regard to word frequency rather than an effect on the long right tail of the distribution. This suggests that frequency does affect all fixations and lends support to models of lexical control in reading. However, an even stronger test would be to retrieve more direct evidence about the latency of lexical processing from neuro-cognitive on-line measures such as ERPs.

There are mixed results and a lot of controversy on frequency effects in ERP. Reported latencies range from 140 ms to 500 ms. The most reliable and well-replicated effects of frequency are N400 effects (e.g. Allen, Badecker, & Osterhout, 2003; Amsel, 2011; Barber et al., 2004; Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Holcomb & Grainger, 2006; Kutas, Van Petten, & Kluender, 2006; Van Petten & Kutas, 1990). Given the average fixation duration of 250 ms and saccadic preparation times, such effects are much too late to be a neuronal correlate of frequency processing which is behaviorally relevant for immediate saccade planning (Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011). Another group of results finds converging evidence for earlier frequency effects between 140-200 ms, mostly identified as the N1 component (Dambacher et al., 2006; Hauk, Davis, Ford, Pulvermuller, & Marslen-Wilson, 2006, 2012; Hauk & Pulvermüller, 2004; Reichle, Tokowicz, Liu, & Perfetti, 2011; Sereno et al., 1998, 2003). There are also findings on the N1 component with a latency between 200-300 ms (Dimigen et al., in prep. Rudell, 1999). Regardless of the large range of latencies, none of the effects seems early enough to impact immediate fixation durations given the estimates derived from oculomotor research.

Reingold and colleagues (2012) argued that frequency effects in natural reading should be found much earlier than in ERP studies because parafoveal preview is not considered in the latter. To test this, they conducted survival analyses on the cumulative fixation distribution to find the earliest point at which these distributions diverge as a function of preview and frequency. They found a frequency effect at 256 ms in fixation behavior in conditions without a valid preview. When a valid preview was available however, the effect showed at 145 ms. The authors conclude that valid preview is the main precondition for frequency effects to be in time to affect fixation times. Since valid preview is the default situation in natural reading, these data support lexical models of oculomotor control in reading. Experiment 3 of this dissertation is concerned with the question whether latency shifts in frequency effects corresponding to the ones found in survival analyses can be found in brain-electric correlates of word processing.

There are some problems with the conception of lexical processing in general and with the use of frequency effects as a marker of lexical access specifically. Schotter et al. (2012) remark that there is no consensus as to what *lexical* properties of a word are. For example, it is usually assumed that there is a *magic moment* of lexical access, when the reader has recognized a given word, but has not yet accessed its meaning (Balota, 1990). Balota and Yap (2006) have argued that the main tasks to measure this magic moment, that is, lexical decision and speeded naming, are frequently influenced by word meaning and thus not accurate. Using word frequency effects in reading as a marker of the magic moment also seems problematic, because – as we have seen – lexical effects are found over an extensive period of time. This temporal extension fits very well with the notion that processing between different linguistic levels overlaps and interacts. For example, Grainger and Holcomb (2009) have interpreted the N400 as a reflection of processing in a 'form-meaning interface', while Williams et al. (2006) have shown that word frequency has an impact on the size of orthographic preview benefits. Moreover, word frequency and sub-lexical features such as initial bigram or trigram frequencies are highly correlated. These interactions between processing levels render the identification of a magic moment of lexical access impossible. Another concern with word frequency is that it is in itself not a clear concept. Different types of frequency are used across studies, such as lemma frequency or word form frequency. These are highly correlated, but might exert their influence at different times (Ford, Marslen-Wilson, & Davis, 2003) as well.

So the question about brain-electric correlates of lexical access (or word recognition) remains open, despite its crucial importance for models of oculomotor control in reading. Frequency effects in ERPs/FRPs can be used to provide a lower bound of when the lexical entry of a word is accessed, but the exact point in time cannot be identified. Above and beyond its merit as a lower bound, frequency is still used in this dissertation because it provides a general indicator of processing difficulty, regardless of the underlying processes.

## 1.3 Saccade execution: ERPs and FRPs

Saccades are an integral part of natural reading. Traditional ERP studies have used the RSVP paradigm to exclude eye movements from the reading process because eye movements lead to artifacts in the EEG signal. The muscle movement of the eyes lead to a myogenic spike potential at saccade onset and the movement of eyeball's corneo-retinal dipole causes large artifacts (see Dimigen et al., 2011, for an in-depth discussion). But the possibility to move ones eyes might have manifold impacts on word processing. The most important difference is probably the fact that reading with saccades is self paced, while the RSVP paradigm uses fixed presentation durations. The commonly used presentation rates in RSVP are usually much slower than fixation and saccade durations in natural reading in order to avoid overlap of processing different words. But such processing overlaps are the default situation in reading.

Furthermore, saccade planning and execution have bearings on attention in two respects. First, attentional resources are generally limited and the necessity to plan eye movements adds another process which requires some of these resources. Second and more specifically, saccade planning is likely to enhance parafoveal processing. The preparation of a saccade is tightly coupled with attention shifts to the target of the saccade (Deubel & Schneider, 1996; Hoffmann & Subramaniam, 1995; Rolfs & Carrasco, 2012). Preparing an eye movement towards a stimulus has been shown to increase the strength of its neural representation in visual brain areas (e.g. Chelazzi, Miller, Duncan, & Desimone, 1993; Sheinberg & Logothetis, 2001; Mazer & Gallant, 2003; Super, van der Togt, Spekreijse, & Lamme, 2004). Also, the target's subjectively perceived contrast is increased (Rolfs & Carrasco, 2012) and detrimental effects of visual crowding are weakened (Pelli, 2008; Pelli & Tillman, 2008). Since the target of a saccade in reading is usually the next word in the parafovea, preview effects should be larger if saccades are executed.

On the other hand, saccades might have negative effects on foveal processing right after a saccade due to saccadic suppression (Temereanca et al., 2012). Temereanca and colleagues compared word list reading with and without saccades in an MEG study and found reduced brain-responses to words that were presented 50 ms after saccade offset as opposed to words presented 600 ms after saccade offset. No such differences were found in reading without saccades. The authors interpreted this as a result of post-saccadic suppression: Visual information uptake is known to be minimal during saccades and lasts 50 ms into the fixation (Matin, 1974; Ross, Morrone, Goldberg, & Burr, 2001). Interestingly, there were no such differences in behavioral performance. Thus, as the authors note themselves, it remains an open question whether saccades are really detrimental or facilitatory to word processing.

Lastly, saccades do not always hit their intended target (Nuthmann, Engbert, & Kliegl, 2005). Such saccadic error is another source of uncertainty that might be detrimental to word processing in natural reading compared to reading in the RSVP paradigm.

This dissertation compares active reading with eye movements (yielding FRPs) to passive reading without eye movements (ERPs) in order to investigate the impact of eye movements on cognitive processes during word recognition. There are also methodological reasons to include an ERP condition into the experiments presented here. First, since the FRP method is rather new, comparative ERP conditions serve to test how well results generalize from ERPs to natural reading. While in the studies in this dissertation the presentation times in ERPs are matched closely to fixation durations in natural reading, the ERP condition still provides a link to prior results. Second, as the timing in ERPs is fixed, stimulus locked effects do not jitter out during averaging and might be visible more clearly than in FRPs. On the one hand, this might provide clues as to the location of effects which are not immediately visible in FRPs. On the other hand, overlapping effects might be easier to separate in FRPs, because the overlap is not always fixed. Thus the paradigms provide complementary advantages. Finally, as Dimigen et al. (2012) point out, ERPs provide an important control condition for identity preview benefit effects. If an identical preview is compared to an unrelated preview in the boundary paradigm, there is a display change in one condition, but not in the other. This might lead to a low-level visual artifact which is confounded with preview benefit effects. In the ERP conditions used in this dissertation, there is always a display change, as the words move across the screen, while the gaze remains in one location. If identity preview effects are also found in ERPs, this would exclude the possibility of a display change artifact.

# 2 The present studies

The present studies integrate traditional ERP research about the time line of visual word recognition with eye movement research on reading. Specifically, the dissertation aims at investigating the impact of eye movements and parafoveal processing on brain-electric correlates of foveal word processing. Also, it uses the more direct on-line insight into actual processing to tackle important questions raised by eye movement research. Chief among these is the timing of lexical processing, which is assumed to drive decisions about when to move the eyes to subsequent words. In a typical boundary paradigm situation, there are three relevant words, whose lexical processing can be studied: The pre-target, the mask and the target. Experiments 1-3 use word list reading to study the frequency of each of these words respectively. All experiments include interactions with effects of parafoveal preview as well as comparisons between active reading with eye movements and passive reading without eye movements.

**Experiment 1** focused on frequency effects of the pre-target word. The main goals were to investigate the preview positivity in more detail and to see if foveal processing load of the pre-target word affects the size of the brain-electric preview effect on the target word, as was previously found in eye movements.

**Experiment 2** focused on frequency effects of the mask. By orthogonalizing the frequency of the mask, the frequency of the target and the validity of the target, we investigated whether there is an effect of the masks frequency. Such an effect has been reported for eye movements and presents an instance of a POF effect.

**Experiment 3** focused on frequency effects of the target word. The main question was how the timing of frequency effects is affected by parafoveal preview. Reingold et al. (2012) predicted that neuronal correlates of frequency effects in natural reading should be visible as early as on fixation onsets with preview.

Experiment 4 focused exclusively on the generalizability of the preview positivity. This experiment used the RSVP-with-flankers paradigm for Chinese sentence reading. A target word in a sentence was either semantically congruent or incongruent with the sentence context both in the parafovea as well as in the fovea. A prior study using this paradigm on English sentence reading had not reported a preview positivity (Barber et al., 2013). So the question arises whether the effect is robust against such changes in reading conditions or limited to our word list paradigm, language, or presentation durations. All of these conditions were tested.

## 2.1 Design and rationale

Since the major part of this dissertation is based on one specific experimental design, this design and its rationale are explained once here. Participants read 500 lists, each consisting of five German nouns, and their task was to detect animal names in those lists. This task has been argued to discourage participants from simple superficial scanning and shallow processing as the meaning of the word needs to be processed (Grainger et al., 2006). The nouns were between four to six letters long and care was taken that word frequency was not confounded with other linguistic variables. 100 lists contained an animal name and were not analyzed. In the remaining 400 lists, each word was used twice, once per experiment half, but the lists were re-shuffled in the second experiment half.

There are three reasons for using word lists over more natural sentence reading. First, words are processed without higher order linguistic processing with regard to the larger context. None of the words can be predicted from prior context and processing beyond word semantics is not necessary. While this sacrifices external validity, it makes experimental control and the range of expected effects more manageable. Second, since there is no predictability from sentence context and there are no short function words, each word will be fixated and no skipping is to be expected. Additionally, we used backward masking to discourage regressive eye movements. The analysis is thus limited to first pass reading. Third, there are four observations per trial, whereas in sentence reading there is usually one observation per trial. This greatly increases statistical power, which is much more of an issue than in traditional eye tracking studies due to the signal to noise ratio of ERPs and FRPs.

Half of the word lists were read with eye movements from left to right using the boundary paradigm (henceforth referred to as *active reading*), the other half was read in variants of the RSVP-with-flankers paradigm. Participants fixated the center of the screen while the word list was moved past their eyes in discrete word-by-word jumps (henceforth called *passive reading*). In experiments 1 and 3 the entire list was visible in passive reading, while in experiment 2 only the immediately preceding and immediately following word

were visible. Active and passive reading were always blocked factors.
Each of the experiments contained a parafoveal preview manipulation. There was always an identity preview (henceforth *valid preview*) which was compared to different kinds of *invalid previews*. The details of the invalid preview manipulations are presented in the specific experiments. Preview was blocked in experiment 3 and randomized in the other studies.
Lastly, all of the words were factored into three different frequency classes (low, medium, and high frequency). Medium frequency words were always in a specific list position and were not analyzed. There were equally many low and high frequency words. All other list positions contained low and high frequency words with equal probability. In experiment 2, low and high frequency words were matched with each other to obtain invalid masks of opposing frequencies. In the second half, this matching was re-shuffled.

## 2.2 Experiment 1: Pre-target frequency and preview

Kornrumpf & Niefind, Sommer, & Dimigen (in press): Active reading is different: Parafoveal preview, saccade execution, and foveal load modulate the brain's response to visual words. *Journal of Cognitive Neuroscience*

The goals of Experiment 1 were to investigate preview effects in ERPs/FRPs in three regards.

1. Preview was manipulated in a graded fashion. There were five levels of preview: The mask either shared no letters with the target or the first one, two or three letters or all letters. The rest of the mask were x's. This allowed us to investigate the impact of single letters on the preview positivity.

2. Preview was compared between active and passive reading to test the impact of saccade planning.

3. We investigated the size of the preview effect in relation to the frequency of the pre-target word. Prior eye movement studies have found reduced preview benefit effects after fixations on words which were difficult to process (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999; White et al., 2005). This has been explained in terms of the foveal load hypothesis. As the foveal word is more difficult to process, attentional resources are recruited from processing of the parafoveal word. We aimed to replicate this dependency of preview effects on attentional resources both in eye movements as well as in the ERPs/FRPs.

We found a preview benefit effect as well as a foveal load effect in first fixation durations, which replicates prior findings from sentence reading (Rayner, 1975; Henderson & Ferreira, 1990). In the FRPs/ERPs, we replicated the preview positivity (Dimigen et al., 2012). Further, we found that the effect was a monotonic function of the amount of parafoveal orthographic information. N1 amplitudes between 160-300 ms were more positive the more preview was available. This effect is consistent with earlier findings that implicate the N1 in orthographic processing (Bentin et al., 1999; Maurer, Brem, et al., 2005; Maurer, Brandeis, & McCandliss, 2005). However, as mentioned before, processing may not be restricted to orthographic processing, but phonological and lexical processing may contribute as well. In FRPs, the preview positivity manifested 160 ms after fixation/stimulus onset and – given our mean fixation duration of 309 ms in list reading – was early enough to be the brain-electric correlate of the behavioral effect. This fits nicely with the fact that in alphabetic script languages orthographic and phonological preview benefits have been found reliably (see Schotter et al., 2012).

The preview positivity was larger in active reading than in passive reading. These results are best explained by pre-saccadic attention shifts (Deubel & Schneider, 1996; Hoffmann & Subramaniam, 1995; Rolfs & Carrasco, 2012) which lead to increased attention in the parafovea. It suggests that saccades exert a facilitatory effect in reading *through* parafoveal processing by enhancing attention to this region of the visual field. Thus, both factors need to be considered in conjunction to fully capture their impact on word recognition.

Another result that showed the strong impact of attention on parafoveal processing was that the preview positivity effect was larger after high frequency pre-target words than after low frequency words. Since high frequency words should be easier to process, foveal load is lower for those and preview effects are larger as a consequence. The foveal load effect has been rather unreliable in prior eye tracking research. It has often only been replicated under certain side-conditions such as spatially close pre-boundary fixations, or only for a subset of participants that remained unaware of display changes (Kennison & Clifton, 1995; Schroyens et al., 1999; White et al., 2005). We found strong evidence in three independent measures, that is, first fixation durations, ERPs and FRPs. Also, the correspondence between EEG and eye tracking measures further supports the notion that the preview positivity is the brain-electric correlate of the preview benefit effect in fixation durations.

Taken together, these results underline the importance of considering characteristics of natural reading in EEG studies on word recognition: Words are not processed in temporal and spatial isolation. Multiple words are visible and processed in parallel during a single fixation (preview and load) and a single word is processed across multiple fixations (due to high saccadic reading rate compared to classical SOAs in ERPs). Processing of adjacent words interacts, because it shares a limited pool of attentional resources.

## 2.3 Experiment 2: Mask frequency and preview

Niefind (under review): Dissociating parafoveal preview benefit and parafovea-on-fovea effects during reading: A combined eye tracking and EEG study.

The second experiment aimed at disentangling the brain-electric correlates of two different forms of parafoveal influences on foveal word recognition: Preview benefits and POF effects. It closely followed up on a study by Risse and Kliegl (2014) who suggested that lexical POF effects are not immediately visible in fixation durations on the pre-target word, but delayed into the subsequent fixation duration and thus usually confounded with preview benefit effects. To separate the influence of the two, the authors ran an eye tracking study in which a target word in each sentence was either masked by itself (valid preview) or by a word of a different frequency (invalid preview): High frequency targets were masked by low frequency masks and vice versa.

This design represents an instance of a three main effects design (Shaffer, 1977; Kliegl, Mayr, Junker, & Fanselow, 1999). As these designs are common in situations with preview validity effects and another instance is also used in experiment 4 of this dissertation, it is instructive to explain the matter in a bit more detail. There are three orthogonal main effects within four conditions, but each of the main effects is mathematically equal to the interaction of the other two: For example, in this study the interaction of the mask and the target frequency is – mathematically and conceptually – the same as preview validity. It is not possible to separate the interaction from the validity main effect, because this would involve conditions, which cannot exist: The target word cannot be of a different frequency than the mask, while the mask is a valid preview of the target at the same time.

In the current design, the frequency of the mask is used as a marker of processing difficulty. Thus, the difficulty of the preview (leading to POF effects) is orthogonal to the validity of the preview (yielding preview benefit effects). Risse and Kliegl (2014) found preview benefit and delayed POF effects on fixation durations on the target word. The goal of this study was to replicate these findings and to investigate their brain-electric correlates in order to get a better insight into the underlying processes. We also looked at the brain-electric correlates of the target frequency. Given the large body of studies and the wide range of latencies at which frequency effects have been observed, it is interesting to see where the effects occur in list reading and also to compare ERPs and FRPs in this regard.

Findings were similar to those of Risse and Kliegl (2014) in fixation durations on the target word. We found a preview validity in all measures and a preview difficulty effect in gaze duration, but not in first and single fixation durations. We also found an effect of target frequency in all measures, which was not reported by Risse and Kliegl. The differences are probably due to the difference between word list and sentence reading.

For the EEG data, we ran a confirmatory analysis based on hypotheses from prior research which focused on the N1 component. In FRPs the N1 component was identified as the segment between 162-238 ms based on global field power (GFP; Lehmann & Skrandies, 1980) and global map dissimilarity (Brandeis, Naylor, Halliday, Callaway, & Yano, 1992) analyses. We replicated a preview positivity for preview validity and found a preview difficulty effect that resembled an N400 effect in relation to the fixation on the pre-target word (Dimigen et al., 2012; Barber et al., 2010, 2013). These results show that there are separable underlying processes for delayed lexical POF effects and preview benefit effects.

No preview effects were found in the N1 segment for ERPs (182-214 ms). The absence of preview effects is probably a result of the combination of the RSVP-with-flankers paradigm with word list reading and our masking conditions. In sentence reading studies, it can be easily seen that the flankers show upcoming and preceding words due to their linguistic link with the central word. In word list reading however, the flankers bear no relation with the central word. On top of this, the left flanker was always masked, while the right flanker word was masked half the time. Participants might not have interpreted the visual input as a word list that is running by their gaze position, as in the other variant used in experiment 1 where clearly an entire block of words moved across the screen. Therefore, participants might not have interpreted the right flanker as a preview of the upcoming word in the center. Such an explanation would entail that attention can be drawn away from the parafoveal flankers and processing can be narrowed down to the foveal word.

In FRPs, a frequency effect with a P2 distribution as described in Dambacher et al. (2006) was found in the N1 segment. Amplitudes were more positive at fronto-central electrode sites for low than for high frequency words and more negative at occipito-temporal electrode sites. The exploratory analysis further showed the effect in the preceding and following GFP-segments, so it lasted from 118-308 ms. In ERPs we did not find a target frequency effect in the N1 segment, but in the exploratory analysis we found

a target frequency effect in the following GFP-segment (214-290) at occipito-temporal electrodes. This finding matched prior findings by Sereno et al. (1998) in scalp distribution, but it was much later than in their study, where it was observed between 132-164 ms. The differences in timing and distribution between the target frequency effects in the two reading paradigms might reflect the difference between frequency effects with and without preview, because there were no preview effects in ERPs. As Reingold et al. (2012) suggested, frequency effects should be found earlier after valid than after invalid previews.
The results further show that words are not processed in isolation when parafoveal information is available. As in experiment 1, the preview positivity found for preview validity probably reflects orthographic and phonological processing. At the same time, the N400 in response to the mask difficulty shows that the parafoveally perceived word is also processed, but at a later processing stage and regardless whether the information is still valid with respect to the foveal target word.

## 2.4 Experiment 3: Target frequency and preview

Dimigen & Niefind, & Schacht (in prep): Timing of word frequency effects in reading as a function of parafoveal preview: Explorations with simultaneous eye-tracking and EEG.

The third experiment focused on target frequency effects after valid and invalid previews. Lexical models of oculomotor control assume that lexical retrieval of a word drives the decision to move the eyes to foveate a new word. The EZ-reader model (Reichle et al., 2006), currently one of the influential models of oculomotor control in reading, makes the even stronger assumption that lexical processing of a word is early enough to influence the immediate fixation duration on this word itself. There are several tight temporal constraints on when frequency must be processed in order to do this. An average fixation during reading lasts around 200-250 ms (Rayner, 1998). Saccadic preparation time in reading has been estimated to take 150-175 ms (Rayner et al., 1983). With the aforementioned non-labile stage lasting 80-100 ms (Becker & Jürgens, 1979), this means that frequency effects should be found before 150-170. Taking the entire saccade preparation time, frequency effects in the brain even need to be found before 75-100 ms. However, upon fixation, visual information takes between 47-73 ms to reach visual cortices where processing begins and visual information encoding has been estimates to take between 78-105 ms (Reichle & Reingold, 2013). Reingold et al. (2012) argue that these temporal constraints do not take parafoveal pre-processing into account. As a consequence, they analyzed cumulative fixation distributions as a function of frequency and preview. The survival analysis used in this study provides a means to gain a more continuous measure of processing than comparing means of fixation durations. They found a frequency effect in eye movements at 256 ms without parafoveal preview and at 145 ms with preview. Given the saccadic preparation times, this suggests that lexical processing in the brain starts at fixation onset if preview is available. Parafoveal pre-processing thus enables direct lexical control of fixation durations.

The main goal of experiment 3 was to replicate these results in eye movements and to see if the brain-electric correlates of frequency processing are indeed shifted by preview. We used x-masks to either provide a full preview of the upcoming word or no preview at all. Furthermore, preview was a blocked factor. The design can thus be viewed as a moving window paradigm study with a window size of either one or two words. Main effects of preview and reading paradigm were not analyzed, as we were only interested in their impact on the frequency effect.

We found a shift in latency of the target frequency effect both in eye movements and ERPs/FRPs. Survival analyses of the first fixation durations showed a divergence point at 210 ms in conditions without preview and at 176 ms with preview. In ERPs/FRPs we found a main effect of frequency at occipito-temporal electrodes between 200-300 ms, replicating earlier findings by Dimigen and colleagues (in prep.). An exploratory analysis with massive testing by means of LMMs at successive 10 ms time windows and all electrodes revealed a temporal shift in this frequency effect as a function of preview, which corresponded almost exactly to the results in the survival analysis: Without preview, the frequency effect began at 210 ms, with preview its onset was at 170 ms. Moreover, between 200-300 ms we also found an interaction in amplitude between preview and frequency, showing that the effect was more pronounced after preview. While these results are in line with the hypothesis that frequency effects are shifted if parafoveal preprocessing is possible, the effect found here is too late to present a plausible neuronal correlate of the effect in eye movement behavior.

The exploratory analysis did also reveal an earlier effect in conditions with preview: Low frequency words elicited more negative amplitudes than high frequency words at occipito-temporal, occipito-parietal and temporal electrodes sites over the left hemisphere between 30-80 ms. This effect needs to be interpreted with caution and should be seen as a starting point for future research, because of the massive amounts of statistical testing without correction for multiple comparisons. Bearing this caveat in mind, the effect is indeed in time to affect the behavioral effect and thus renders the assumption of direct lexical control on oculomotor behavior during reading plausible. Note that our findings are not at odds with any competing theoretical assumptions. Moreover, we found no evidence of a corresponding effect at a later latency in conditions without preview. Thus, a plausible brain-electric correlate of the target frequency effect without preview in fixation durations is missing. Further research is necessary to shed more light into the matter: The most promising next step in this regard is to investigate frequency effects as a function of preview in sentence reading. Since the exact timings of effects in behavior and brain seem to be affected by the use of word list reading, results from sentence reading can be related to prior research more clearly.

There were no clear differences between active and passive reading. The early frequency effect was larger and lasted longer in ERPs than FRPs. The most plausible explanation at this point is that the effect might have smeared out in FRPs due to the temporal jitter caused by varying fixation durations as opposed to a stable presentation duration in ERPs.

## 2.5 Experiment 4: Preview effects in Chinese sentence reading

Li & Niefind, Sommer, Wang, & Dimigen (2015): Parafoveal processing in reading Chinese sentences: Evidence from event-related brain potentials., *Psychophysiology, 52*(10), 1361-1347.

This experiment focused on the preview positivity and investigated whether it is robustly found under radically different conditions. Furthermore, we aimed to show N400 effects of parafoveally presented semantic congruency violations with strict eye movement control and in Chinese. So far, these effects have been found in German and English (Barber et al., 2010, 2013). Both of these studies used the RSVP-with-flankers paradigm (one flanker on each side) to investigate parafoveal processing in sentence reading. In Barber et al. (2010), the target word was congruent in the fovea, but was sometimes replaced by an incongruent word while it was still in the parafoveal position. In Barber et al. (2013), the target word could be incongruent or congruent both in the parafoveal or in the foveal position, thus separating parafoveal and foveal congruency. Both studies found an N400 effect of parafoveal congruency, the latter study also found an effect of foveal congruency. However, none of the two studies used an eye tracker to ensure that participants' gaze remained in the screen center. Thus, the parafoveal N400 effects might really be the result of foveal processing after moving the eyes. A straight saccade would be visible in the electro-oculogram (EOG) which was used for fixation control in the studies. Slow drifts, however, are not necessarily detected using the EOG.

Importantly, in either study, an identity preview effect should manifest both as a preview positivity as well as a late N400 effect (Dimigen et al., 2012). Such an effect should have been visible as an interaction between parafoveal and foveal congruency because the design used in Barber et al. presents another instance of a three main effects design. We hypothesized that the effect vanished due to the particular presentation durations and ISI used in the previous studies: Barber and colleagues presented the words for 100 ms only and compared an ISI of 150 or 350 ms. On the one hand, the word presentation might be too short to elicit preview effects (Kliegl, Hohenstein, Yan, & McDonald, 2013; Schroyens et al., 1999). On the other hand, the long ISI might be so long that the effects have vanished already (Pernet, Uusvuori, & Salmelin, 2007).

We employed the design of Barber et al. (2013) with a few crucial changes. First, we used Chinese sentences. Chinese is written in a non-alphabetic script and Chinese readers have shown strong parafoveal processing (e.g. Yan et al., 2009). Second, across two experiments we manipulated the presentation durations in order to compare a setting close to Barber et al.'s (word duration 100 ms, ISI 180 ms) to more reading-like presentation durations (word duration 250 ms, ISI 30 ms), while keeping the overall SOA (280 ms) constant. Lastly, we did not include sentence constraint as a factor, but only controlled it experimentally. In their short presentation durations condition (which is close to ours), Barber and colleagues found parafoveal N400 effects for highly constraining sentence contexts only.

We found a preview positivity which was unaffected by presentation durations. This result shows that the preview positivity is robust across presentation durations, languages and writing systems as well as word list and sentence reading. The most likely explanation why Barber and colleagues did not find the effect, was that they did not sample the EEG signal from deep posterior electrodes which are close to the neural source of the N1 (Maurer, Brandeis, & McCandliss, 2005). Furthermore, the use of a mastoid reference is likely to attenuate the effect as – due to their position – the mastoid electrodes may contain some of it themselves.

We replicated the finding of a parafoveal N400 effect under conditions of strong eye movement control. This result lends credence to the effects originally reported by Barber et al. (2010) and Barber et al. (2013). The fact that we found this effect regardless of presentation rate and with sentences of medium constraint is in line with the notion that Chinese readers exhibit stronger parafoveal processing. A direct comparison between high and low constraint sentences would be needed to further support this hypothesis though.

Lastly, in relation to fixation onset on the foveal target word, we found effects of foveal congruency as well as an N400 effect of preview. This effect was only marginally significant in FRPs in Dimigen et al. (2012). Therefore, this study was the first to find the effect in ERPs and presented the first replication of the effect in general.

# 3 General Discussion

The present dissertation used co-registration of EEG and eye tracking to study brain-electric correlates of word processing during reading under more natural circumstances often ignored in traditional ERP studies. Words were not processed in relative temporal and spatial isolation customary to prior ERP research by using slow presentation rates and showing one word at a time. Instead, in ERPs reading like presentation rates were used and parafoveal flankers were shown. In FRPs, reading was self paced by allowing eye movements, thus adding saccade planning and execution to the coordinative task of reading naturally. The main questions of interest were the brain-electric correlates of parafoveal preview and interactions with the lexical properties of pre-target, mask and target. Moreover, the impact of eye movements was investigated by comparing event and fixation related brain potentials. Results concerning all three goals will be discussed in turn. Limitations and outlooks are discussed along the way.

## 3.1 Parafoveal preview modulates the brain-electric correlates of word processing

Unlike in many ERP studies, in natural reading the processing of a word does usually not begin when it is foveated. A main contribution to bridging gaps between the reading research of eye tracking and ERP communities is the exploration of brain-electric correlates of preview validity effects. Three of the experiments described here found a preview positivity, an effect of preview validity on the falling flank of the N1 component most pronounced over occipito-temporal electrodes sites with a slight lateralization to the left hemisphere. Experiment 1 showed that the effect is sensitive to the amount of valid orthographic information available in the parafovea. Moreover, the strong correspondence with the preview benefit in fixation durations as well as the effect's latency suggests that the preview positivity is directly underlying the behavioral preview effect. Experiment 2 separated the effect from lexical costs of the mask, which showed as a delayed POF effect (cf. section 3.2). Experiment 4 further showed the robustness of the preview positivity when it was replicated in a study on Chinese sentence reading, that is, in a different language and writing system as well as with contextual predictability. Can the features of the preview positivity give us more detailed information about the underlying mechanisms of the preview benefit? The large body of research on the N1 does suggest an early and automatic mapping from orthography to phonology (cf. section 1.1.2, Kutas et al., 2006). If orthographic features are already partially identified in the parafovea, subsequent processing is faster and more efficient. This relates very well to eye tracking evidence from alphabetic script languages which have consistently found orthographic and also phonological preview benefit effects. However, it has been suggested that such a mapping is not necessarily the driving factor of preview benefits in Chinese (Yan et al., 2009), where the findings for preview benefits differ somewhat. Due to the pictographical nature of Chinese characters, it is possible that the robust semantic preview benefits observed in Chinese readers reflect a more direct mapping from orthography to meaning. If the underlying processing mechanism is different, one should expect the effect of preview to differ in latency or scalp distribution.

An alternative explanation for the underlying mechanisms of the preview positivity is closely related to the question whether preview validity effects actually reflect benefits or artificial processing costs. We have already mentioned processing costs of the parafoveal mask itself, but here we are concerned with costs caused by the change in retinal input across saccades: Readers generate expectations of what the retinal input should look like after the saccade. Such expectations are met in everyday reading, but not in boundary paradigms with invalid previews. The predictive coding framework (Friston, 2005; Rao & Ballard, 1999) claims that humans constantly generate predictions of likely sensory input, while the actual sensory input generates an error signal, that is, the mismatch between the input and the predictions (Rao & Ballard, 1999). Such predictions reduce processing load, as attention can be allocated specifically to unexpected sensory input while expected input can be handled more efficiently[1]. The preview positivity bears some resemblance with a visual mismatch negativity, which has been interpreted as a prediction error feedback signal (Friston, 2005; Stefanics, Kremlacek, & Czigler, 2014). Therefore, it is not clear whether the preview positivity actually reflects a processing benefit due to parafoveal pre-processing (which could also be viewed as trans-saccadic priming) or processing costs due to violations of predictions about the post-saccadic retinal input. The latter interpretation is consistent with the fact that the preview positivity looks similar in Chinese, even though different underlying word processing mechanisms might be at work.

Regardless of the underlying mechanisms, the preview positivity shows that parafoveal

[1] Note that this idea has also been used in neural network models of language processing (Elman, 1990)

information is used and has a strong impact on subsequent foveal word recognition. Predictions of retinal input after the saccade cannot be generated from language context in our word list studies, but must be based on the parafoveal input before saccades. It is reasonable to assume that if parafoveal information is routinely processed during reading, it is of value to the efficiency of the reading process. Thus, regardless of potential costs of the boundary paradigm, it serves to illustrate the beneficial effect of parafoveal pre-processing.

A methodological issue with preview arises from the orthogonal manipulation of parafoveal and foveal information: The interaction of foveal and parafoveal information is mathematically equal to the preview effect. This was the case in experiments 2 and 4 in this dissertation. There have been some recent examples of studies with three main effect designs (Risse & Kliegl, 2014) as well as theoretical discussions on the value of such designs (Kliegl et al., 1999; Shaffer, 1977).

While I feel that if the factor preview is involved, these designs are the best possible solution, they confound factors. The crucial question is whether the interaction of two main effects is a third main effect conceptually or whether it just takes the same mathematical design vector in a model. In experiment 4, for example, it is perfectly possible that foveal congruency is not processed if the target word was identified as incongruent with the sentence context in the parafovea. This would lead to an interaction such that there is a foveal congruency effect after parafoveally congruent masks, but not after incongruent ones. This interaction is conceptually different from a process that matches parafoveal and foveal input (i.e., preview validity effect). However, disentangling the two mathematically would require conditions that are not possible: There can be no condition where the parafoveal word is incongruent with the sentence context, but congruent during foveal presentation while the preview is valid. Likewise, in experiment 2 there can be no condition where the target word is of high frequency and the mask of low frequency, but the preview is valid. Thus, the designs used are the best solution there is. A possible remedy for the problem using ERPs/FRPs is that previous studies provide knowledge of what the main effects look like in space and time. In our cases, the preview positivity was already known from previous research and the timing and locus of the effect were replicated.

## 3.2 Complex interactions between foveal and parafoveal processing of adjacent words

Under natural circumstances, a word is not processed in isolation. Foveal and parafoveal processing of adjacent words overlap and interact. Here, we investigated the interactions of foveal and parafoveal word processing by using word frequency as an estimation of processing difficulty of a word in general (experiment 1 and 2) and word frequency effects as marker of the critical moment when a word is recognized, that is, lexical access (experiment 3).

Experiment 2 showed that parafoveal processing difficulty influences foveal fixation durations. Lexical POF effects have been a matter of controversy because they have been expected to affect the immediate fixation in which the word is parafoveally visible. We replicated findings by Risse and Kliegl (2014) showing that lexical POF effects do exist, but are delayed into subsequent fixations. We were able to separate POF effects from preview benefit effects within the same fixation duration. Preview difficulty elicited an N400 effect which suggests that parafoveal word identification starts before fixation onset on the word. Given that N400 effects are usually considered to reflect the end of single word reading, that is, meaning retrieval, the results show that a word can be fully processed based on parafoveal presentation.

Experiment 1 showed that foveal and parafoveal processing draw on a limited pool of attentional resources. If foveal processing is difficult, less attention is allocated to parafoveal word recognition. This foveal load effect was shown in ERPs and FRPs for the first time. Thus, even without higher-level linguistic coherence between words as in sentence reading, the processing of a single word is impacted by its surrounding context.

This interaction of adjacent words' foveal processing via parafoveal preview is also relevant because preview alters the time course of foveal word processing: Experiment 3 showed that word recognition is faster if a valid parafoveal preview was provided. Taken together, these results show that realistic data about word recognition during reading need to take into account that multiple words are processed during a single fixation and that a single word is processed across multiple fixations.

The ERP/FRP data provide insights that go beyond the corresponding eye tracking results: The most obvious example is the fact that we found an N400 effect of preview difficulty at the same latency as a preview positivity in Experiment 2. Prior ERP research has implicated the N400 in post-lexical processing of word meaning, while the N1 has been implicated for orthographic processing. If specific ERP/FRP effects can be mapped to stages of word recognition, these stages can be related to behavioral effects in much more detail, further specifying the eye-mind link and making testable predictions about models of oculomotor control in reading. The current results provide some evidence that words are processed in parallel, at least at different processing stages. Currently, results are compatible with models of oculomotor control which propose serial processing of words (Reichle et al., 2006) as well as parallel word processing (Schad & Engbert, 2012), but combining ERP and eye tracking research is a promising method to settle this important question.

Traditional ERP studies often use slow presentation rates to avoid overlapping brain potentials to adjacent stimuli. In our studies, such overlap has been accepted. Some control analyses were run to show that effects are not the result of processing related to subsequent fixations, but mostly it has been trusted that averaging will remove unwanted variance. Experiment 3 took the averaging approach further and used linear mixed effect models to obtain a more thoroughly cleaned estimate of the event/fixation related brain response. A major step in solving the overlap problem more cleanly will be to use generalized linear models and deconvolution methods to separate overlapping brain responses as is common in event related fMRI research (Dandekar, Privitera, Carney, & Klein, 2012; Dale, 1999).

## 3.3 Eye movements and reading paradigm

In the introduction, possible detrimental and facilitatory effects of saccades on reading have been discussed. Results from experiment 1 strongly suggest that saccades have a facilitatory effect on word recognition, which is missed if only foveal processing is taken into account. Saccades are accompanied by attention shifts (Deubel & Schneider, 1996; Hoffmann & Subramaniam, 1995; Rolfs & Carrasco, 2012) and enhanced sensitivity to visual features in the destined target area of the saccade (Chelazzi et al., 1993; Sheinberg & Logothetis, 2001; Mazer & Gallant, 2003; Super et al., 2004). Unless a word is re-fixated, the target of the saccade is a new word which is usually in the parafovea. Thus, saccades enhance parafoveal pre-processing, which in turn impacts subsequent foveal processing. Like the foveal load findings, this result shows the dependency of parafoveal processing on attention. More importantly, it presents another factor that has been ignored in traditional ERP studies on reading and that advocates co-registration of eye movements and FRPs in reading research.

However, ERPs and FRPs showed very similar component structures and effects in most of our studies. The strongest differences were due to the temporal jitter caused by different fixation durations in FRPs, while ERP responses always overlap in the same way. The differential overlap is a prerequisite for deconvolution procedures mentioned as a promising future methodological advance. However, it can also lead to masking effects by smearing them in time, as has been seen in experiment 3. Despite these differences, the general correspondence between ERPs and FRPs shows that previous ERP research has captured many crucial aspects of word recognition and provides a wealth of evidence that future FRP studies can build on.

The experiments presented here all focused on first pass reading. Future studies need to extend these finding towards other common eye movement patterns such as skipping and regressions. For example, Metzner, von der Malsburg, Vasishth, and Rösler (submitted) recently found P600 effects specifically in sentences with syntactic and semantic violations, but the P600 was limited to trials with regressive eye movements. As the P600 has been viewed as a marker of re-analysis (Friederici, Hahne, & Mecklinger, 1996), this result provides converging evidence from different methodologies.

At last, the most obvious direction for further research is clearly the use of sentences as linguistic material rather than word lists. Specifically in theoretical matters such as the exact latency of frequency effects, only completely natural reading conditions can provide a definite answer. Experiment 4 in this dissertation took a first step in this direction and showed fairly consistent results concerning the preview positivity. More research is needed to extend the other findings to sentence reading as well.

## 3.4 Conclusion

This dissertation has investigated the brain-electric correlates of word recognition under natural reading conditions, that is, parafoveal preview, saccade execution, and the temporal and spatial rate of overlap. Under such conditions it has provided consistent insights into the complex interplay of parafoveal and foveal word processing both in eye movement behavior and fixation/event related brain potentials. Furthermore, it has extended a body of research showing that co-registration of eye tracking and EEG is a promising step towards relating eye tracking and ERP research of the past 40 years.

# 4 Original Articles

1. Kornrumpf, B.*, Niefind, F.*, Sommer, W., & Dimigen, O. (in press): Active reading is different: Parafoveal preview, saccade execution, and foveal load modulate the brain's response to visual words. *Journal of Cognitive Neuroscience*

2. Niefind, F. (under review in *Psychophysiology*): Dissociating parafoveal preview benefit and parafovea-on-fovea effects during reading: A combined eye tracking and EEG study.

3. Dimigen, O.*, Niefind, F.*, & Schacht, A. (in prep): Timing of word frequency effects in reading as a function of parafoveal preview: Explorations with simultaneous eye-tracking and EEG.

4. Li, N.*, Niefind, F.*, Sommer, W., Wang, S., & Dimigen, O. (2015): Parafoveal processing in reading Chinese sentences: Evidence from event-related brain potentials. *Psychophysiology, 52*(10), 1361-1347. doi:10.1111/psyp.12502

*Authors contributed equally to the project

# Bibliography


Allen, M., Badecker, W., & Osterhout, L. (2003). Morphological analysis in sentence processing: an erp study. *Language and Cognitive Processes*, *18*(4), 405–430. doi:10.1080/01690960244000054

Allison, T., McCarthy, G., Nobre, A., Puce, A., & Belger, A. (1994). Human extrastriate visual cortex and the perception of faces, words, number, and colors. *Cerebral Cortex*, *4*(5), 544–554. doi:10.1093/cercor/4.5.544

Amsel, B. D. (2011). Tracking real-time neural activation of conceptual knowledge using single-trial event-related potentials. *Neuropsychologia*, *49*(5), 970–983.

Angele, B. & Rayner, K. (2011). Parafoveal processing of word n+2 during reading: do the preceding words matter? *Journal of Experimental Psychology-Human Perception and Performance*, *37*(4), 1210–1220. doi:10.1037/a0023096

Angele, B., Slattery, T. J., Yang, J., Kliegl, R., & Rayner, K. (2008). Parafoveal processing in reading: manipulating n+1 and n+2 previews simultaneously. *Visual Cognition*, *16*(6), 697–707. doi:10.1080/13506280802009704

Ashby, J. & Rayner, K. (2004). Representing syllable information during silent reading: evidence from eye movements. *Language and Cognitive Processes*, *19*(3), 391–426. doi:10.1080/01690960344000233

Auer, P. (2000). On-line-syntax - oder: was es bedeuten könnte, die zeitlichkeit der mündlichen sprache ernst zu nehmen. *Sprache und Literatur*, *85*, 43–56.

Baccino, T. & Manunta, Y. (2005). Eye-fixation-related potentials: insight into parafoveal processing. *Journal of Psychophysiology*, *19*(3), 204–215. doi:10.1027/0269-8803.19.3.204

Balota, D. A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology*, *17*(3), 364–390. doi:10.1016/0010-0285(85)90013-1

Balota, D. A. (1990). The role of meaning in word recognition. In D. A. Balota, F. d'Arcais, & K. Rayner (Eds.), *Comprehension processes in reading* (pp. 9–32). Hillsdale, NJ: Lawrence Earlbaum Associates, Inc.

Balota, D. A. & Yap, M. J. (2006). Attentional control and the flexible lexical processor: explorations of the magic moment of word recognition. *From inkmarks to ideas: Current issues in lexical processing*, 229–258.

Barber, H. A., Donamayor, N., Kutas, M., & Münte, T. (2010). Parafoveal n400 effect during sentence reading. *Neuroscience Letters*, *479*(2), 152–156. doi:10.1016/j.neulet.2010.05.053

Barber, H. A., van der Meij, M., & Kutas, M. (2013). An electrophysiological analysis of contextual and temporal constraints on parafoveal word processing. *Psychophysiology*, *50*(1), 48–59. doi:10.1111/j.1469-8986.2012.01489.x

Barber, H. A., Vergara, M., & Carreiras, M. (2004). Syllable-frequency effects in visual word recognition: evidence from erps. *Neuroreport*, *15*(3), 545–548. doi:10.1097/01.wnr.0000111325.38420.80

Becker, W. & Jürgens, R. (1979). An analysis of the saccadic system by means of double-step stimuli. *Vision Research*, *19*(9), 967–983. doi:10.1016/0042-6989(79)90222-0

Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). Erp manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution. *Journal of Cognitive Neuroscience*, *11*(3), 235–260. doi:10.1162/089892999563373

Brandeis, D., Naylor, H., Halliday, R., Callaway, E., & Yano, L. (1992). Scopolamine effects on visual information processing, attention, and event-related potential map latencies. *Psychophysiology*, *29*(3), 315–336.

Briihl, D. & Inhoff, A. W. (1995). Integrating information across fixations during reading - the use of orthographic bodies and of exterior letters. *Journal of Experimental Psychology-Learning Memory and Cognition*, *21*(1), 55–67. doi:10.1037/0278-7393.21.1.55

Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, *363*(6427), 345–347.

Dale, A. M. (1999). Optimal experimental design for event-related fmri. *Human Brain Mapping*, *8*(2-3), 109–114. doi:10.1002/(sici)1097-0193(1999)8:2/3⟨109::aid-hbm7⟩3.0.co;2-w

Dambacher, M., Kliegl, R., Hofmann, M., & Jacobs, A. M. (2006). Frequency and predictability effects on event-related potentials during reading. *Brain Research*, *1084*, 89–103. doi:10.1016/j.brainres.2006.02.010

Dandekar, S., Privitera, C., Carney, T., & Klein, S. A. (2012). Neural saccadic response estimation during natural viewing. *Journal of Neurophysiology*, *107*(6), 1776–1790. doi:10.1152/jn.00237.2011

Deubel, H. & Schneider, W. X. (1996). Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vision Research*, *36*(12), 1827–1837. doi:10.1016/0042-6989(95)00294-4

Deubel, H., O'Regan, J. K., & Radach, R. (2000). Attention, information processing and eye movement control. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 355–376). Oxford UK: Elsevier.

Deutsch, A., Frost, R., Pollatsek, A., & Rayner, K. (2005). Morphological parafoveal preview benefit effects in reading: evidence from hebrew. *Language and Cognitive Processes*, *20*(1-2), 341–371. doi:10.1080/01690960444000115

Dimigen, O., Dambacher, M., Kliegl, R., Sommer, W., & Hauk, O. (in prep.). Multiple loci of the word frequency effect revealed by combined eye-tracking and eeg.

Dimigen, O., Kliegl, R., & Sommer, W. (2012). Trans-saccadic parafoveal preview benefits in fluent reading: a study with fixation-related brain potentials. *Neuroimage*, *62*(1), 381–393. doi:10.1016/j.neuroimage.2012.04.006

Dimigen, O., Sommer, W., Hohlfeld, A., Jacobs, A. M., & Kliegl, R. (2011). Coregistration of eye movements and eeg in natural reading: analyses and review. *Journal of Experimental Psychology-General*, *140*(4), 552–572. doi:10.1037/a0023885

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology-Human Perception and Performance*, *31*(5), 954–969.

Drieghe, D. (2011). Parafoveal-on-foveal effects on eye movements during reading. In S. P. Liversedge, I. Gilchrist, & S. Everling (Eds.), *The oxford handbook of eye movements* (pp. 839–855). Oxford: Oxford University Press. doi:10.1093/oxfordhb/9780199539789.013.0046

Drieghe, D., Rayner, K., & Pollatsek, A. (2008). Mislocated fixations can account for parafoveal-on-foveal effects in eye movements during reading. *Quarterly Journal of Experimental Psychology*, *61*(8), 1239–1249. doi:10.1080/17470210701467953

Elman, J. L. (1990). Finding structure in time. *Cognitive science*, *14*(2), 179–211. doi:10.1016/0364-0213(90)90002-E

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). Swift: a dynamical model of saccade generation during reading. *Psychological Review*, *112*(4), 777–813. doi:10.1037/0033-295x.112.4.777

Ford, M. A., Marslen-Wilson, W. D., & Davis, M. H. (2003). Morphology and frequency: contrasting methodologies. In H. R. Baayen & R. Schreuder (Eds.), *Morphological structure in language processing* (pp. 89–124). Berlin - New York: Mouton de Gruyter.

Frazier, L. & Rayner, K. (1982). Making and correcting errors during sentence comprehension: eye movements in the analysis of structurally ambiguous sentences. *Cognitive psychology*, *14*(2), 178–210. doi:10.1016/0010-0285(82)90008-1

Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). Temporal structure of syntactic parsing: early and late event-related brain potential effects. *Journal of Experimental Psychology-Learning Memory and Cognition*, *22*(5), 1219–1248. doi:10.1037/ /0278-7393.22.5.1219

Friston, K. J. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *360*(1456), 815–836. doi:10.1098/rstb.2005.1622

Grainger, J., Kiyonaga, K., & Holcomb, P. J. (2006). The time course of orthographic and phonological code activation. *Psychological Science*, *17*(12), 1021–1026. doi:10.1111/j.1467-9280.2006.01821.x

Grainger, J. & Holcomb, P. J. (2009). Watching the word go by: on the time-course of component processes in visual word recognition. *Language and linguistics compass*, *3*(1), 128–156. doi:10.1111/j.1749-818X.2008.00121.x

Hauk, O., Coutout, C., Holden, A., & Chen, Y. (2012). The time-course of single-word reading: evidence from fast behavioral and brain responses. *Neuroimage*, *60*(2), 1462–1477. doi:10.1016/j.neuroimage.2012.01.061

Hauk, O., Davis, M. H., Ford, M., Pulvermuller, F., & Marslen-Wilson, W. D. (2006). The time course of visual word recognition as revealed by linear regression analysis of erp data. *Neuroimage*, *30*(4), 1383–1400. doi:10.1016/j.neuroimage.2005.11.048

Hauk, O. & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clinical Neurophysiology*, *115*(5), 1090–1103. doi:10.1016/j.clinph.2003.12.020

Henderson, J. M. & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading - implications for attention and eye-movement control. *Journal of Experimental Psychology - Learning Memory and Cognition*, *16*(3), 417–429. doi:10.1037/0278-7393.16.3.417

Henderson, J. M. & Ferreira, F. (1993). Eye movement control during reading: fixation measures reflect foveal but not parafoveal processing difficulty. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *47*(2), 201. doi:10.1037/h0078814

Hoffmann, J. E. & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*(6), 787–795. doi:10.3758/BF03206794

Hohenstein, S. & Kliegl, R. (2014). Semantic preview benefit during reading. *Journal of Experimental Psychology-Learning Memory and Cognition*, *40*(1), 166–190. doi:10.1037/a0033670

Hohenstein, S., Laubrock, J., & Kliegl, R. (2010). Semantic preview benefit in eye movements during reading: a parafoveal fast-priming study. *Journal of Experimental Psychology - Learning Memory and Cognition*, *36*(5), 1150–1170. doi:10.1037/a0020233

Holcomb, P. J. & Grainger, J. (2006). On the time course of visual word recognition: an event-related potential investigation using masked repetition priming. *Journal of Cognitive Neuroscience*, *18*(10), 1631–1643.

Inhoff, A. W. (1987). Parafoveal word perception during eye fixations in reading - effects of visual salience and word structure. *Attention and Performance*, (12), 403–418.

Inhoff, A. W. (1989a). Lexical access during eye fixations in reading - are word access codes used to integrate lexical information across interword fixations. *Journal of Memory and Language*, *28*(4), 444–461. doi:10.1016/0749-596x(89)90021-1

Inhoff, A. W. (1989b). Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology-Human Perception and Performance*, *15*(3), 544–555. doi:10.1037//0096-1523.15.3.544

Inhoff, A. W. (1990). Integrating information across eye fixations in reading: the role of letter and word units. *Acta Psychologica*, *73*(3), 281–297. doi:10.1016/0001-6918(90)90027-d

Inhoff, A. W. & Liu, W. M. (1998). The perceptual span and oculomotor activity during the reading of chinese sentences. *Journal of Experimental Psychology-Human Perception and Performance*, *24*(1), 20–34. doi:10.1037/0096-1523.24.1.20

Inhoff, A. W., Starr, M., & Shindler, K. L. (2000). Is the processing of words during eye fixations in reading strictly serial? *Perception & Psychophysics*, *62*(7), 1474–1484. doi:10.3758/bf03212147

Inhoff, A. W. & Tousman, S. (1990). Lexical priming from partial-word previews. *Journal of Experimental Psychology-Learning Memory and Cognition*, *16*(5), 825–836. doi:10.1037/0278-7393.16.5.825

Johnson, R. L., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading: evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology-Human Perception and Performance*, *33*(1), 209–229. doi:10.1037/0096-1523.33.1209

Kennedy, A. (1998). The influence of parafoveal words on foveal inspection time: evidence for a processing trade-off. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 149–179). Oxford: Elsevier.

Kennedy, A. (2000). Parafoveal processing in word recognition. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology*, *53*(2), 429–455. doi:10.1080/027249800390556

Kennedy, A. & Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. *Vision Research*, *45*(2), 153–168. doi:10.1016/j.visres.2004.07.037

Kennedy, A., Pynte, J., & Ducrot, S. (2002). Parafoveal-on-foveal interactions in word recognition. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology*, *55*(4), 1307–1337. doi:10.1080/02724980244000071

Kennison, S. M. & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working-memory capacity readers - implications for eye-movement control. *Journal of Experimental Psychology - Learning Memory and Cognition*, *21*(1), 68–81. doi:10.1037/0278-7393.21.1.68

Kliegl, R., Hohenstein, S., Yan, M., & McDonald, S. A. (2013). How preview space/time translates into preview cost/benefit for fixation durations during reading. *Quarterly Journal of Experimental Psychology*, *66*(3), 581–600. doi:10.1080/17470218.2012.658073

Kliegl, R., Mayr, U., Junker, M., & Fanselow, G. (1999). Testing age invariance in language processes. In S. Kemper & R. Kliegl (Eds.), *Constraints on language: aging, grammar, and memory.* (pp. 137–167). New York, NY: Springer.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: the influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology-General*, *135*(1), 12–35. doi:10.1037/0096-3445.135.1.12

Kutas, M., Van Petten, C., & Kluender, R. (2006). Psycholinguistic electrified ii (1994-2005). In M. A. Gernsbacher & M. Traxler (Eds.), *Handbook of psycholinguistics* (2nd, pp. 659–724). New York: Elsevier Press.

Lehmann, D. & Skrandies, W. (1980). Reference-free identification of components of checkerboard-evoked multichannel potential fields. *Electroencephalography and Clinical Neurophysiology*, *48*(6), 609–621.

Lima, S. D. & Inhoff, A. W. (1985). Lexical access during eye fixations in reading - effects of word-initial letter sequence. *Journal of Experimental Psychology-Human Perception and Performance*, *11*(3), 272–285. doi:10.1037/0096-1523.11.3.272

Matin, E. (1974). Saccadic suppression - review and analysis. *Psychological Bulletin*, *81*(12), 899–917.

Maurer, U., Blau, V. C., Yoncheva, Y. N., & McCandliss, B. D. (2010). Development of visual expertise for reading: rapid emergence of visual familiarity for an artificial script. *Developmental Neuropsychology*, *35*(4), 404–422. doi:10.1080/875656412010480916

Maurer, U., Brandeis, D., & McCandliss, B. D. (2005). Fast, visual specialization for reading in english revealed by the topography of the n170 erp response. *Behavioral and brain functions : BBF*, *1*, 13–13. doi:10.1186/1744-9081-1-13

Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience*, *17*(10), 1532–1552. doi:10.1162/089892905774597218

Maurer, U., Rossion, B., & McCandliss, B. D. (2008). Category specificity in early perception: face and word n170 responses differ in both lateralization and habituation properties. *Frontiers in Human Neuroscience*, *2*. doi:10.3389/neuro.09.018.2008

Mazer, J. A. & Gallant, J. L. (2003). Goal-related activity in v4 during free viewing visual search: evidence for a ventral stream visual salience map. *Neuron*, *40*(6), 1241–1250.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, *7*(7), 293–299. doi:10.1016/s1364-6613(03)00134-7

McClelland, J. L. (1979). On the time relations of mental processes: an examination of systems of processes in cascade. *Psychological review*, *86*(4), 287.

McConkie, G. W. & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *17*, 578–586. doi:10.3758/BF03203972

McConkie, G. W. & Rayner, K. (1976). Asymmetry of perceptual span in reading. *Bulletin of the Psychonomic Society*, *8*(5), 365–368. doi:10.3758/BF03335168

McConkie, G. W. & Yang, S. (2003). How cognition affects eye movements during reading. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: cognitive and applied aspects of eye movement research* (pp. 413–427). Oxford, Uk: Elsevier.

Metzner, P., von der Malsburg, T., Vasishth, S., & Rösler, F. (submitted). The importance of reading naturally: evidence from combined recordings of eye movements and electric brain potentials.

Miellet, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: visual acuity does not modulate the perceptual span in reading. *Psychological Science*, *20*(6), 721–728. doi:10.1111/j.1467-9280.2009.02364.x

Nobre, A. C., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature*, *372*(6503), 260–263. doi:10.1038/372260a0

Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research*, *45*(17), 2201–2217. doi:10.1016/j.visres.2005.02.014

Pelli, D. G. (2008). Crowding: a cortical constraint on object recognition. *Current Opinion in Neurobiology*, *18*(4), 445–451.

Pelli, D. G. & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience*, *11*(10), 1129–1135.

Pernet, C., Uusvuori, J., & Salmelin, R. (2007). Parafoveal-on-foveal and foveal word priming are different processes: behavioral and neurophysiological evidence. *Neuroimage*, *38*(2), 321–330. doi:10.1016/j.neuroimage.2007.07.035

Pollatsek, A., Lesch, M., Morris, R. K., & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. *Journal of Experimental Psychology-Human Perception and Performance*, *18*(1), 148–162. doi:10.1037/0096-1523.18.1.148

Pollatsek, A., Reichle, E. D., Juhasz, B. J., Machacek, D., & Rayner, K. (2008). Immediate and delayed effects of word frequency and word length on eye movements in reading: a reversed delayed effect of word length. *Journal of Experimental Psychology - Human Perception and Performance*, *34*(3), 726–750. doi:10.1037/0096-1523.34.3.726

Pollatsek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in the perceptual span for israeli readers. *Brain and language*, *14*(1), 174–180. doi:10.1016/0093-934X(81)90073-0

Rao, R. P. N. & Ballard, D. H. (1999). Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nature Neuroscience*, *2*(1), 79–87. doi:10.1038/4580

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*(1), 65–81. doi:10.1016/0010-0285(75)90005-5

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. doi:10.1037/0033-2909.124.3.372

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, *62*(8), 1457–1506. doi:10.1080/17470210902816461

Rayner, K., Castelhano, M. S., & Yang, J. (2009). Eye movements and the perceptual span in older and younger readers. *Psychology and Aging*, *24*(3), 755–760. doi:10.1037/a0014300

Rayner, K. & Duffy, S. A. (1986). Lexical complexity and fixation times in reading - effects of word-frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, *14*(3), 191–201. doi:10.3758/bf03197692

Rayner, K., Li, X. S., Juhasz, B. J., & Yan, G. L. (2005). The effect of word predictability on the eye movements of chinese readers. *Psychonomic Bulletin & Review*, *12*(6), 1089–1093. doi:10.3758/bf03206448

Rayner, K., McConkie, G. W., & Zola, D. (1980). Integrating information across eye-movements. *Cognitive Psychology*, *12*(2), 206–226.

Rayner, K., Slowiaczek, M. L., Clifton, C., & Bertera, J. H. (1983). Latency of sequential eye movements: implications for reading. *Journal of Experimental Psychology-Human Perception and Performance*, *9*(6), 912–922. doi:10.1037/0096-1523.9.6.912

Rayner, K. & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*(4417), 468–469. doi:10.1126/science.504987

Rayner, K., Juhasz, B. J., & Brown, S. J. (2007). Do readers obtain preview benefit from word n+2? a test of serial attention shift versus distributed lexical processing models of eye movement control in reading. *Journal of Experimental Psychology-Human Perception and Performance*, *33*(1), 230–245. doi:10.1037/0096-1523.33.1.230

Reichle, E. D., Pollatsek, A., & Rayner, K. (2006). E-z reader: a cognitive-control, serial-attention model of eye-movement behavior during reading. *Cognitive Systems Research*, *7*(1), 4–22. doi:10.1016/j.cogsys.2005.07.002

Reichle, E. D. & Reingold, E. M. (2013). Neurophysiological constraints on the eye-mind link. *Frontiers in Human Neuroscience*, *7*, 361–361.

Reichle, E. D., Tokowicz, N., Liu, Y., & Perfetti, C. A. (2011). Testing an assumption of the e-z reader model of eye-movement control during reading: using event-related potentials to examine the familiarity check. *Psychophysiology*, *48*(7), 993–1003. doi:10.1111/j.1469-8986.2011.01169.x

Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: evidence from a survival analysis of fixation durations. *Cognitive Psychology*, *65*(2), 177–206. doi:10.1016/j.cogpsych.2012.03.001

Risse, S. & Kliegl, R. (2014). Dissociating preview validity and preview difficulty in parafoveal processing of word n+1 during reading. *Journal of Experimental Psychology-Human Perception and Performance*, *40*(2), 653–668. doi:10.1037/a0034997

Rolfs, M. & Carrasco, M. (2012). Rapid simultaneous enhancement of visual sensitivity and perceived contrast during saccade preparation. *Journal of Neuroscience*, *32*(40), 13744–13753. doi:10.1523/jneurosci.2676-12.2012

Ross, J., Morrone, M. C., Goldberg, M. E., & Burr, D. C. (2001). Changes in visual perception at the time of saccades. *Trends in Neurosciences*, *24*(2), 113–121.

Rossion, B., Joyce, C. A., Cottrell, G. W., & Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. *Neuroimage*, *20*(3), 1609–1624. doi:10.1016/j.neuroimage.2003.07.010

Rudell, A. P. (1999). The recognition potential and the word frequency effect at a high rate of word presentation. *Brain research. Cognitive brain research*, *8*(2), 173–5. doi:10.1016/S0926-6410(99)00018-X

Rugg, M. D. (1985). The effects of semantic priming and word repetition on event related potentials. *Psychophysiology*, *22*(6), 642–647. doi:10.1111/j.1469-8986.1985.tb01661.x

Rugg, M. D. (1987). Dissociation of semantic priming, word and non-word repetition effects by event-related potentials. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology*, *39*(1), 123–148. doi:10.1080/02724988743000060

Schad, D. & Engbert, R. (2012). The zoom lens of attention: simulating shuffled versus normal text reading using the swift model. doi:10.1080/13506285.2012.670143

Schendan, H. E., Ganis, G., & Kutas, M. (1998). Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms. *Psychophysiology*, *35*(03), 240–251. doi:10.1111/1469-8986.3530240

Schotter, E. R. (2013). Synonyms provide semantic preview benefit in english. *Journal of Memory and Language*, *69*(4), 619–633.

Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention Perception & Psychophysics*, *74*(1), 5–35. doi:10.3758/s13414-011-0219-2

Schroyens, W., Vitu, F., Brysbaert, M., & d'Ydewalle, G. (1999). Eye movement control during reading: foveal load and parafoveal processing. *Quarterly Journal of Experimental Psychology Section a - Human Experimental Psychology*, *52*(4), 1021–1046. doi:10.1080/713755859

Sereno, S. C., Brewer, C. C., & O'Donnell, P. J. (2003). Context effects in word recognition: evidence for early interactive processing. *Psychological Science*, *14*(4), 328–333. doi:10.1111/1467-9280.14471

Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: evidence from eye movements and event-related potentials. *Neuroreport*, *9*(10), 2195–2200. doi:10.1097/00001756-199807130-00009

Shaffer, J. (1977). Reorganization of variables in analysis of variance and multidimensional contingency tables. *Psychological Bulletin*, *84*, 220–228.

Sheinberg, D. L. & Logothetis, N. K. (2001). Noticing familiar objects in real world scenes: the role of temporal cortical neurons in natural vision. *Journal of Neuroscience*, *21*(4), 1340–1350.

Simola, J., Holmqvist, K., & Lindgren, M. (2009). Right visual field advantage in parafoveal processing: evidence from eye-fixation-related potentials. *Brain and Language*, *111*(2), 101–113. doi:10.1016/j.bandl.2009.08.004

Slattery, T. J., Angele, B., & Rayner, K. (2011). Eye movements and display change detection during reading. *Journal of Experimental Psychology-Human Perception and Performance*, *37*(6), 1924–1938. doi:10.1037/a0024322

Stefanics, G., Kremlacek, J., & Czigler, I. (2014). Visual mismatch negativity: a predictive coding view. *Frontiers in Human Neuroscience*, *8*. doi:10.3389/fnhum.2014.00666

Super, H., van der Togt, C., Spekreijse, H., & Lamme, V. A. F. (2004). Correspondence of presaccadic activity in the monkey primary visual cortex with saccadic eye movements. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(9), 3230–3235.

Tanaka, J. W. & Curran, T. (2001). A neural basis for expert object recognition. *Psychological Science*, *12*(1), 43–47. doi:10.1111/1467-9280.00308

Tarkiainen, A., Helenius, P., Hansen, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain*, *122*, 2119–2131. doi:10.1093/brain/122.11.2119

Temereanca, S., Haemaelaeinen, M. S., Kuperberg, G. R., Stufflebeam, S. M., Halgren, E., & Brown, E. N. (2012). Eye movements modulate the spatiotemporal dynamics of word processing. *Journal of Neuroscience*, *32*(13), 4482–4494. doi:10.1523/jneurosci.5571-11.2012

Van Petten, C. & Kutas, M. (1990). Interactions between sentence context and word frequency in event-related brain potentials. *Memory and Cognition*, *18*(4), 380–393. doi:10.3758/BF03197127

White, S. J. (2008). Eye movement control during reading: effects of word frequency and orthographic familiarity. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(1), 205. doi:10.1037/0096-1523.34.1.205

White, S. J., Rayner, K., & Liversedge, S. P. (2005). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: a reexamination. *Psychonomic Bulletin & Review*, *12*(5), 891–896. doi:10.3758/BF03196782

White, S. J., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2008). Eye movements when reading transposed text: the importance of word-beginning letters. *Journal of Experimental Psychology-Human Perception and Performance*, *34*(5), 1261–1276. doi:10.1037/0096-1523.34.5.1261

Williams, C. C., Perea, M., Pollatsek, A., & Rayner, K. (2006). Previewing the neighborhood: the role of orthographic neighbors as parafoveal previews in reading. *Journal of Experimental Psychology-Human Perception and Performance*, *32*(4), 1072–1082. doi:10.1037/0096-1523.32.4.1072

Yan, M., Risse, S., Zhou, X., & Kliegl, R. (2012). Preview fixation duration modulates identical and semantic preview benefit in chinese reading. *Reading and Writing*, *25*(5), 1093–1111. doi:10.1007/s11145-010-9274-7

Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2009). Readers of chinese extract semantic information from parafoveal words. *Psychonomic Bulletin & Review*, *16*(3), 561–566. doi:10.3758/pbr.16.3.561

Yang, J., Wang, S., Tong, X., & Rayner, K. (2012). Semantic and plausibility effects on preview benefit during eye fixations in chinese reading. *Reading and Writing*, *25*(5), 1031–1052. doi:10.1007/s11145-010-9281-8

Yen, M.-H., Tsai, J.-L., Tzeng, O. J. L., & Hung, D. L. (2008). Eye movements and parafoveal word processing in reading chinese. *Memory & Cognition*, *36*(5), 1033–1045. doi:10.3758/mc.36.5.1033

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# Eidesstattliche Erkärung

Hiermit erkläre ich an Eides statt,

1. dass ich die vorliegende Arbeit selbständig und ohne unerlaubte Hilfe verfasst habe,
2. dass ich mich nicht anderwärts um einen Doktorgrad beworben habe und noch keinen Doktorgrad der Psychologie besitze,
3. dass mir die zugrunde liegende Promotionsordnung vom 3. August 2006 bekannt ist.

Berlin, den

Florian Niefind